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FINAL TECHNICAL REPORT.
Secretary of the Navy Chair in Oceanography

ONR Grant N00014-85-J-1239
27 July 1992

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This covers the period 1 October 1985 to 30 September 1990. (The fifth year covers a no-cost extension of the original four year grant.)

Let me outline the subjects on which I worked during the five year period.

RESEARCH ACTIVITIES

1. OCEAN ACOUSTIC TOMOGRAPHY. This is a field started by Wunsch (who occupied one of the four Chairs) and Munk to use acoustics for studying the ocean temperature and current field. In 1988, the Navy supported a transition of this field from a research effort to operational applications. In 1986, we worked successfully on using reciprocal transmissions for measuring currents. In 1986 we measured vorticity in a sing-around a 1000 km triangle in the North East Pacific. In summer 1988 we installed six moorings in the Greenland Sea, and these were recovered the following summer after having been covered by ice. With transmission every 4 hours for a year, this is by far the best sampled set of measurements as to what happens in the water column when the sea freezes. We started our work on "Moving Ship Tomography" as a means of improving the resolution. To our amazement we learned that the traditional Chen & Millero equations of state used for determining sound speed were seriously in error. Finally we participated with the Navy on a "High Gain Initiative" as an application of tomography to large aperture receivers.

2. THE HEARD ISLAND EXPERIMENT. Near the end of the five year period we were fully occupied with preparation for a global experiment to test the feasibility of measuring greenhouse ocean warming by mean of long-range acoustic transmissions. The experiment itself was conducted in January 1991, and involved eight countries, and successful transmission from a source in the Indian Ocean to receivers in all ocean basins.

3. SATELLITE IMAGERY RESEARCH This resulted in a paper on the visibility of surface vessels from satellites, both S.A.R. and in the visible.

COMMITTEES

Under the terms of the Navy Chair, we were encouraged to engage in activities to help foster the close relations between the Navy and civilian ocean communities.

1. JASON. I worked on a month each summer on DoD activities. My efforts were concentrated on acoustic and non-acoustic ASW work, and some broader Navy activities. This includes working on several committees which were concerned with classified issues. During the five years we made some contributions in this field.

2. OCEAN STUDIES BOARD of the NATIONAL ACADEMY OF SCIENCES. I served as chairman of this board until 1988, and then continued as chairman of the Navy Panel. During this period the Board was able to assist numerous navy activities, and collaborated closely with the Chiefs of Naval Research.

3. MONTEREY BAY AQUARIUM RESEARCH INSTITUTE (MBARI). This Institute, founded by David Packard, is revolutionizing remote sensing in the oceans. I have been a member of the Board since the Institute was founded in 1987.

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4. MAX-PLANCK INSTITUTE FOR METEOROLOGY, HAMBURG, SCIENTIFIC ADVISORY BOARD. I served on the board 1986 to 1991. This was of great advantage in connection with the effort on climate modeling associated with the Heard Island Experiment.

SELECTED TALKS AND RELATED ACTIVITIES:

1986

Honorary Degree, Cambridge University.
Bakerian Lecture, The Royal Society of London.
Four invited lectures, The People's Republic of China.

1987

IUGG Meeting, Vancouver, B. C.
Victor Paul Starr Memorial Lecture, MIT.
Visited the USSR to discuss the Greenland Sea Experiment and gave invited lecture at the Soviet Academy of Sciences, Moscow.

1988

"Global Acoustics: A way to study ocean climate." European Geophysical Society, Bologna, Italy.

1989

"Review of Tomography," CSIRO Marine Laboratory, Hobart, Tasmania, Australia. February through May 1989.

"Long-term acoustic monitoring of ocean temperature," CCCO Meeting, Nova Scotia Canada.

Invited participation at the Inaugural meeting of The Oceanography Society, Monterey, CA.

1990

Dinner talk at the Symposium on Tactical Oceanography, Naval Postgraduate School, Monterey, CA.

Michelson Lecture, "Acoustic Tomography," U. S. Naval Academy, Annapolis, MD.

"Acoustic Monitoring of Global Ocean Warming," NATO Workshop, La Spezia, Italy.

PUBLICATIONS:

Munk, W. and C. Wunsch. Biases and caustics in long-range acoustic tomography. *Deep-Sea Research*, 32:11, 1317-1346, 1985.

W. Munk and C. Wunsch. Bias in Acoustic Travel Time through an Ocean with Adiabatic Range-Dependence. *Geophys. and Astrophys. Fluid Dynamics*, 39:1-24, 1987.

Munk, W., F. Zachariasen and P. Scully-Power. Ships from Space. *Proceedings of The Royal Society*, 412:231-254, 1987.

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- Howe, B. M. and W. H. Munk. Deep-sea moorings in a tidal current. *Deep-Sea Research*, **35**:111-119, 1988.
- Citation for Gordon Hamilton. Invited presentation at AGU, Baltimore, MD, 21 May 1987, *Eos, Trans. Am. Geophys. Union*, **68**:32, 677, 1988.
- Munk, W. H. and D. M. Farmer. Bringing Physical and Biological Observations into Harmony. In: *Toward a Theory on Biological-Physical Interactions in the World Ocean*, ed. B. J. Rothschild, 549-554. Holland: Kluwer Academic Publishers. Invited paper presented at: NATO Advanced Research Workshop, 1-5 June 1987, Chateau de Bonas, Gers, France, 1988.
- Munk, W. H. and P. F. Worcester. Ocean Acoustic Tomography. *Oceanography*, **1**:8-10, 1988.
- Munk, W. H., W. C. O'Reilly and J. L. Reid. Australia-Bermuda sound transmission experiment (1960) revisited. *J. Phys. Oceanogr.*, **18**:1876-1898, 1988.
- Methods for Exploring the Large Scale Ocean Turbulence. Invited paper presented at: Symposium on Perspectives in Fluid Mechanics in honor of Hans-Wolfgang Liepmann, held at California Institute of Technology, Pasadena, California, 10-12 January 1985. In: *Perspectives in Fluid Mechanics*, Donald Coles (ed.), 1-13. New York: Springer-Verlag, 1988.
- Munk, W. and P. Worcester. An Oceanographic Time Capsule. *Oceanography*, **2**:48-49, 1989.
- Cornuelle, B., W. Munk and P. F. Worcester. Ocean Acoustic Tomography from Ships. *J. Geophys. Res.*, **94**:6232-6250, 1989.
- Munk, W. and A. M. G. Forbes. Global Ocean Warming: An Acoustic Measure? *J. Phys. Oceano.*, **19**:1765-1778, 1989.
- Global Ocean Warming: Detection by Long-Path Acoustic Travel Time. *Oceanography*, **2**(2):40-41, 1989.
- Closing Remarks at the Inaugural Meeting of The Oceanography Society, Monterey, CA, 27-30 August 1989. *Oceanography*, **2**(2):57, 1989.
- Acceptance of the 1989 Bowie Medal. AGU, San Francisco, CA, 6 December 1989. *EOS, Trans. Am. Geophys. Union*, **71**:1, 13, 1990.
- Long term acoustic monitoring of ocean temperature. Invited paper presented at: CCCO, held at Halifax, Nova Scotia, 14-20 June 1989 *SCOR-IOC/CCCO-X/3*, 14-15, 1989.
- Davis, R., M. Gregg, J. Katz, W. Munk, D. Nelson, F. Perkins and J. Vesecky. Sea Surface Films. JASON Tech. Rpt. No. JSR-86-105, 1989.
- Greenland Sea Project Group. A Venture Toward Improved Understanding of the Oceans' Role in Climate. *Eos*, 12 June 1990.
- Munk, W., R. Revelle, P. Worcester and M. Zumberge. Strategy for future measurements of sea level. *National Academy of Sciences Press*, 221-227, 1990.
- Dinner Talk at the Symposium on Tactical Oceanography, Naval Postgraduate School, Monterey, CA. 13 March 1990. (Unpublished)

Refraction of Sound Waves at Polar Latitude. *J. Geophysical Research*, 96:4, 7015-7022, 1991.

Munk, W. and F. Zachariasen. Refraction of Sound by Islands and Seamounts. *J. Atmospheric and Oceanic Technology*, 8:4, 554-574, 1991.

Bermuda Shadow. Presented at The Robert W. Stewart Symposium, Victoria, BC, 25-26 May 1990. *Atmosphere-Ocean*, 29:2, 183-196, 1991.

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